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The principles of reducing temperature measurement uncertainty of modern thermal imaging system

Abstract. *The aim of the present study is to investigate the reasons of temperature measurement uncertainty when using modern thermal imaging systems. The basic requirements for high-temperature thermal imaging technique, that can improve the accuracy of determining the temperature of the heated body, are formulated.*

Streszczenie. *Celem niniejszej pracy jest badanie przyczyn niepewności pomiaru temperatury przy użyciu nowoczesnych systemów termowizyjnych. Sformułowano podstawowe wymagania dotyczące techniki obrazowania termicznego w zakresie wysokich temperatur, spełnienie których poprawi dokładność pomiaru temperatury ogrzewanego ciała. (**Zasady zmniejszenia niedokładności pomiaru we współczesnym systemie termowizyjnym**)*

Keywords: non-contact high temperature measurements, three-colour thermal imager, uncertainty of the temperature measurement.
Słowa kluczowe: bezdotykowe pomiary wysokotemperaturowe, trójkolorowa kamera termowizyjna, niepewność pomiaru temperatury.

Introduction

There is the problem of determining the temperature of the heated metals in industrial processes. The most convenient methods are the contactless methods for temperature measurement, which are based on the registration of the thermal radiation from the surface of the heated products [1–3]. The development of microelectronic technologies has made it possible to start serial production of the low-cost thermal imaging techniques [4–6]. Today, many consumers can use thermal imaging equipment for adjustment and control of the high-temperature manufacturing processes. Application of thermal imagers in difficult production conditions is much more effective than pyrometry techniques. Functional capabilities of modern thermal imaging techniques give a false impression of simplicity to her application. Actually often there are difficult conditions of temperature measurement when the thermal emissivity $\varepsilon(\lambda, T)$, where T – temperature and λ – wavelength, is heterogeneous on the surface of bodies and dynamically varies over time. Special measures for the correct interpretation of the values the actual temperature in these cases are required [6].

For example, the spectral emissivity of the metals changes significantly during the heating process [7, 8]. Their surface at high temperatures is rapidly oxidized by atmospheric oxygen, in contrast to many dielectrics. This leads to considerable uncertainty $\varepsilon(\lambda, T)$. The influence of angle β between the normal to the test surface of the body and the viewing direction on the measured temperature is observed. The fluctuations of heat flows of radiation and noise matrix photo detectors lead to significant fluctuations of the maximum measured values of the temperature of objects with the image size of a few pixels.

The total temperature measurement error is caused by a number of reasons that are discussed in detail in [9]. Reducing their impact can be achieved while respecting basic principles, that must be followed when designing and applying the thermal imaging equipment.

Basic principles to reduce uncertainty of temperature measurement

To understand the ways to improve the accuracy of temperature measurement, one should know the features of thermal imaging technique. The producers of thermal imagers usually do not inform consumers about these features. The basic principles, that reduce the uncertainty of the temperature measurements, necessary to observe during designing a of high-temperature thermal imagers. The following conditions should be ensured:

– the minimizing of uncertainty of temperature measurements, which is achieved by optimal selection of spectral plots of thermal radiation registration;
– the ability to measure the actual temperature T and to evaluate the effective thermal emissivity ε_{ef};
– the determination of the maximum temperature $T_{\max}$ of the bodies and its time dependence $T_{\max}(t)$, that is necessary during the control of many thermal technical processes;
– the invariance of results of maximum temperature $T_{\max}$ measurement to the change dimensions of the image of bodies whose temperature is controlled;
– the invariance of the measured values $T_{\max}$ to the nonstationarity of the noise variance of photo detector matrix, i. e. dependence of the noise on the value of incident thermal flux.

Selection of spectral regions in which the thermal radiation should be registered

Component of the error of temperature measurement, caused by the uncertainty of the value ε_{ef}, depends on the used range of the spectrum of thermal radiation registration. Dependencies of the relative error of temperature measurement for standard regions of the spectrum, that are used the thermal imaging systems, can be obtained by numerical methods (Fig. 1) [6]. These curves demonstrate the need of careful choice of the spectral region of thermal radiation registration in case of uncertainty of the effective coefficient of thermal radiation [10]. For example, temperature measurement in the range of 800-1500°C should be conducted by means of the thermal imaging devices which detect thermal radiation in the range of 0.7-0.8 μm. In this case the uncertainty of the temperature measurement can be reduced by an order of magnitude compared to the thermal imagers, which use the region of 8-14 microns.

The accuracy of temperature measurement of bodies with known and stable values ε_{ef} is provided by dividing the measured signal by the value ε_{ef}. Therefore, manufacturers of infrared thermal-imaging cameras of mid infrared spectral region (3-5 and 8-14 μm) often extend the range of measured temperatures up to 2000 or even 3000°C. Correction of temperature readings taking into account the value ε_{ef} is often difficult in practice. For example, the oxide film, which arises during heating of metals up to high temperatures, is growing unequally. This leads to nonstationary values ε_{ef} and their inhomogeneity across the surface. Obviously, the incipient uncertainty ε_{ef} greatly reduces the accuracy of measurement of current temperature of ferrous metals, heated up to high temperatures in a normal air environment. Therefore, the use of infrared thermal-imaging cameras of mid infrared spectral region in such cases is ineffective. Manufacturers of modern thermal imagers based on micro bolometer arrays often result advice on the determination ε_{ef}, that are not suitable for high temperatures.

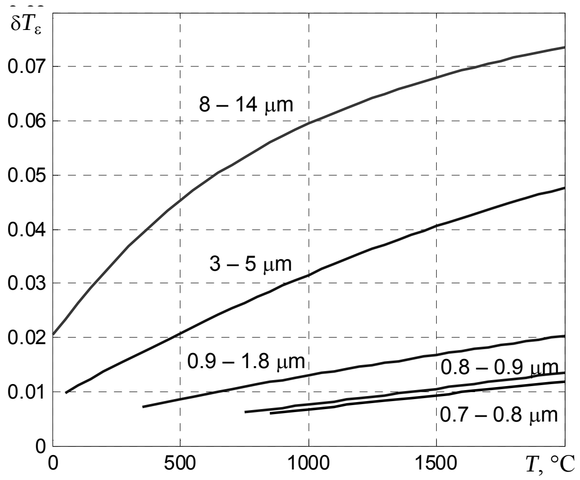

Fig.1. Temperature dependencies of the relative errors of true temperature determination obtained by the partial radiation thermal imagers using typical spectral bands for relative uncertainty of ε value equal to 0.1

Accounting of effective thermal emissivity ε_{ef}

The vast majority of modern of pyrometers and thermal imagers carry out measurement of the thermal radiation in a limited part of the spectrum. The measured temperature in cases of uncertainty ε_{ef}, t. e., assuming that ε_{ef} = 1, is called to temperature of partial radiation T_{pr} [2, 3]. Almost all bodies have ε_{ef} < 1. Therefore the temperature of the partial radiation T_{pr} is always less than the actual temperature T_a. For example, if the effective temperature emissivity is ε_{ef} = 0.5, a detectable signal U_s is two times less than the signal from the black body of the same temperature T_a (Fig. 2).

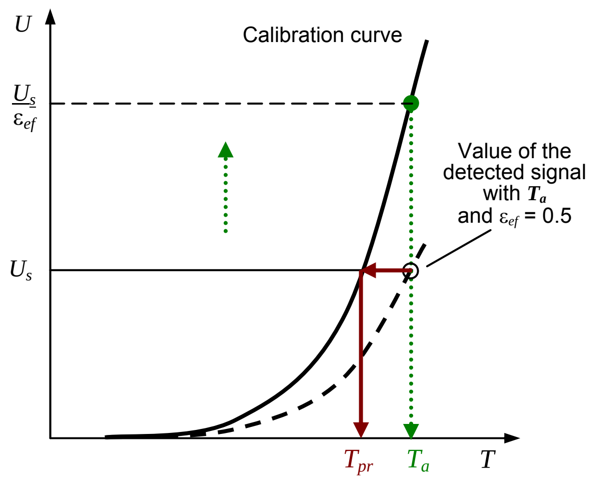

Fig.2. A typical form of calibration curve (solid line) and dependence value of the detected signal from the temperature T of the body with an effective thermal emissivity ε_{ef} = 0.5 (dashed line)

In cases, where it is known beforehand value ε_{ef}, the measured signal is divided by the value ε_{ef}. This operation makes it possible to define the actual temperature T_a (Fig. 2).

About 15% of modern pyrometers measure the heat flows in two regions of the spectrum. The calculation the ratio of these signals for blackbody radiation at high temperatures allows you to get a calibration dependence, the approximate form of which is shown in Fig. 3. It slowly changes with temperature and has a weak nonlinearity. This calibration curve is used to determine the spectral-ratio temperature T_{sr} [2, 6]. The slope of the Planck function is high on its shortwave wing. Therefore the spectral ratio pyrometers of near infrared region spectrum are often used to measure the temperature of heated metals.

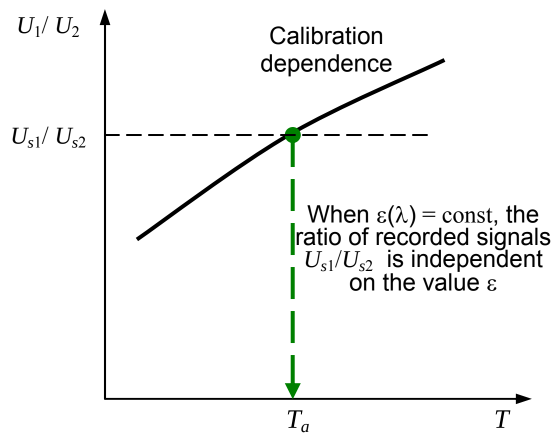

Fig.3. A typical form of calibration dependence when using spectral-ratio temperature T_{sr}

The peculiarity of this conditional temperature is independence of result of determining the temperature of "gray" bodies, for which $\varepsilon(\lambda)$ = const, on the values of thermal emissivity ε. Values of spectral-ratio temperature T_{sr} for $\varepsilon(\lambda) \neq$ const will be overstated for metals and understated for dielectrics [6]. Therefore for determination of the actual temperature T_a it is necessary to know the ratio $\varepsilon_{ef1}/\varepsilon_{ef2}$.

Determining the actual temperature T_a in cases, where there is no information about the magnitude of ε, is possible, when measuring the thermal radiation in three regions of the spectrum. When using additional condition on the behavior of function $\varepsilon(\lambda)$, for example,

$$\varepsilon(\lambda) = \varepsilon_2 \exp\left[b(\lambda - \lambda_2)\right], \tag{1}$$

where ε_2 – the thermal emissivity at a wavelength λ_2, b - the slope of depending $\varepsilon(\lambda)$, you can create a system of three nonlinear equations, the solution of which will enable the determination of ε_{ef} or T_a [6, 11-15]. For example, the system of three equations, when the dependence of the velocity ν = = D/τ on recorded digital signal D rise is used, will be the following [6]

$$\begin{cases} \nu_1 = \varepsilon_2\left[1 + b\mu_1(T)\right]F_1(T), \\ \nu_2 = \varepsilon_2\left[1 + b\mu_2(T)\right]F_2(T), \\ \nu_3 = \varepsilon_2\left[1 + b\mu_3(T)\right]F_3(T), \end{cases} \tag{2}$$

where τ is frame exposure time, $F_i(T)$ are calibration dependencies of ν_i values on the temperature of the absolute black body model (at ε = 1, b = 0), $\mu_I(T)$ are dependencies of the contribution of the slop of $\varepsilon(\lambda)$ (that is value b) into the signal rise velocities $\nu_i(T)$.

Determination of the time dependence of the maximum temperature of bodies

The values of the measured temperature of even uniformly heated bodies depend on the inhomogeneity of the distribution of the thermal emissivity $\varepsilon(\lambda, x, y)$. The oxide film usually grows with the formation of uneven spots of dross. The thickness of this oxide film influences the $\varepsilon(\lambda,x,y)$ and the measured temperature value $T(,x,y)$, respectively. The surface temperature of spots is smaller since the heat conductivity of the oxide is low. Therefore for determination of the temperature of the body surface it is necessary to use the purest surface areas that have the highest brightness of thermal radiation.

Angle β between the normal to controllable surface of the body and the observation direction also affects the measured values T. Metals are not Lambertian emitters that causes the dependence of brightness of thermal radiation on the angle β. It is difficult to take into account these angles are. Note that the points of the thermogram of uniformly heated body, for which the $\beta = 0$, generally have higher values T. When setting up the heating process, it is difficult all the time to keep track of areas of the body, where the temperature field has a maximum. Therefore the algorithm of processing of the thermal image frames should contain block selection portions of the surface with maximum brightness. These portions should be used in determining the maximum temperature $T_{\max}$.

The algorithm for determining the maximum temperature $T_{\max}$ should be based on the statistical processing of the right high-temperature edge of histograms of obtained thermal images [6]. This necessarily includes knowledge of the dependencies of the standard deviation of fluctuations $\sigma_{\Sigma k}$ of registered in the k-th spectral region signals D_k on the speed of their changes $V_k = D_k/\tau$. These dependencies should be determined in the process of calibration of thermal imaging devices using blackbody model. The mean value of the digital signals $\bar{D}_k$ on the right edge of the histograms is determined by a special algorithm taking into account the $\sigma_{\Sigma k}$ and V_k [16]. The maximum temperature $T_{\max}$ is calculated by the values $\bar{V}_k = \bar{D}_k / \tau$.

If the time dependence of $T_{\max}(t)$ is determined by the maximum values of registrable temperature field, there is the considerable of values $T_{\max}(t)$, because it does not take into account the statistical nature of the formation of the thermal image. To address this shortcoming it is recommended to use an algorithm of statistical averaging of the brightest points of the thermal image of each frame [16]. When using this algorithm the scatter of calculated values $T_{\max}(t)$ is significantly reduced.

Ensuring invariance T_{max} with respect to size of controlled bodies and nonstationarity of noise of photo detectors

Thermal images always contain "stuck" pixels. Their influence on the obtained values of the maximum temperature $T_{\max}(t)$ is particularly noticeable at small sizes images of bodies. To reduce their impact a correction of thermal images with use of maps of "stuck" pixels or median filtering can be carried out. In this case, the signals of «stuck» pixels are replaced by the median of neighboring pixels. When measuring high temperatures, i.e. at high levels of registered heat flow, clusters "hot" pixels are formed. They can not be completely eliminated by using the median filtering. Therefore the algorithm of determining $T_{\max}(t)$ should be supplemented by special operations. They should discard of the possible noise emissions, when determining $\bar{D}_{k\max}$.

These algorithms should take into account the difference of statistical parameters of fluctuations thermal radiation of the controlled object and the formation of clusters of "hot" pixels. For example, unpleasant feature of the photo detectors of high-temperature three-colour thermal imager [6, 15] there is the strong increase in the number of "hot" pixels (they are brighter than neighboring pixels), when flux of thermal radiation (T > 1400 °C) is big. Moreover, their contribution to the total signal increases with temperature. Therefore during its calibration the dependence of the standard deviation noises $\sigma_{\Sigma k}\left(\bar{V}_k\right)$, which allows you to select the correct interval averaging on the right high-temperature edge of the histograms is determined. When determining the value of $\bar{D}_{k\max}$ the number of points of the thermal image, that fall within the averaging interval, and the dependence $\sigma_{\Sigma k}\left(\bar{V}_k\right)$ should be considered.

The implementation of the proposed solutions in the algorithms of thermograph of high-temperature three-colour thermal imager [6] has allowed providing the weak influence of the sizes of the image monitored of objects on the measurements of maximum temperature $T_{\max}(t)$. Also a weak dependence $T_{\max}(t)$ on the nonstationarity of fluctuations signals $\sigma_{\Sigma k}\left(\bar{V}_k\right)$ is provided.

The effectiveness of the proposed solutions can estimate by analyzing Fig. 3 and Fig. 4a. These illustrations shows the temperature fields of a tungsten coil of lamp, which obtained using three-colour thermal imager. The tungsten coil of lamp has the shape of a cone with the diameter of 3 mm at the base. The temperature field in Fig. 3 has been recorded at a short distance (about 30 cm) to the lamp. Therefore, the thermal image of a tungsten coil of lamp has enough resolution. To display the temperature field palette Jet is used. The temperature of the tungsten coil varies in a wide range from 750 to 950°C. You may notice that most of hot plots of the tungsten coil are located in its middle.

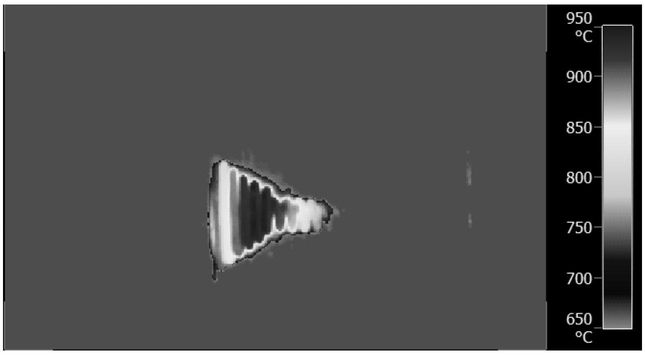

Fig. 3. The temperature field of tungsten coil of lamp, obtained using the three-colour thermal imager [6]

Image of tungsten coil of the lamp decreases by several times, when the lamp is located at a distance of 2 m. The original thermogram of tungsten spiral of this lamp in the narrower range of temperature display is shown in Fig. 4. Two serial images of the temperature field of this spiral, which increased 4 times, are placed in Fig. 4a is higher than the original image of spiral. Approximately 15 pixels of these images are in the temperature range 925-945 °C. The pixels of temperature field that are outside of the temperature range are displayed in gray. It is seen that the pixel values of temperature field are fluctuated from frame to frame. The smoothed histograms D_k of these images, which are registered in three regions of the spectrum, are shown in Fig. 4*b*. The vertical dashed lines indicate the calculated values $\bar{D}_{k\,\max}$. Obviously, the maximum temperature of partial radiation $T_{pr2\max}$, is calculated at a few pixels of the image. The hottest region of the tungsten spiral is narrow. Therefore, thermal radiation of this region fluctuates noticeably. However, the scatter of indications T_{pr2max} (t) in the second spectral portion is only ±2 °C (Fig. 4*c*).

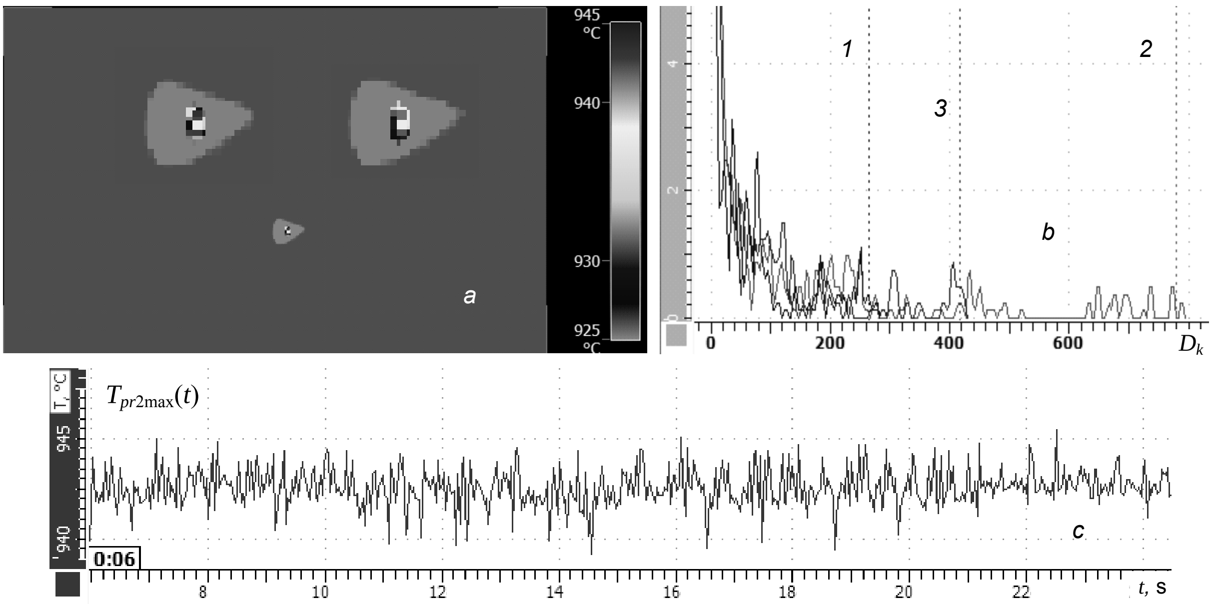

Fig.4. The temperature field of tungsten coil of lamp in the narrower temperature range (925-945 °C) (*a*), smoothed histogram of signals recorded in the three regions of the spectrum (*b*) and the obtained dependence $T_{pr2\max}(t)$ (*c*)

Summary

Thus, the described principles of reducing of uncertainty of temperature measurement allows to create high-temperature thermal imaging devices with features that will adequately meet the requirements of consumers.

The use of these devices will increase the accuracy of temperature measurement in difficult cases, when there is the inhomogeneity of thermal emissivity, uneven heating and so on. Therefore specialists of engineering and metallurgical enterprises should wider use the thermal imaging devices in the technological control systems. The cost of modern high-temperature imaging systems is approached by the price of the pyrometers. But the efficacy of thermal imaging systems use much higher.

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